GEOPOTENTIAL RESEARCH MISSION

— SCIENTIFIC RATIONALE —

Report of the
Geopotential Research Mission
Science Steering Group

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THE GEOPOTENTIAL RESEARCH MISSION

SCIENTIFIC RATIONALE

by

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SUMMARY

The Geopotential Research Mission (GRM) is designed to measure variations in the gravity and magnetic field over the entire globe to a resolution of 100 km with unprecedented completeness and accuracy. The mission consists of two satellites at 160 km altitude in polar orbits.

The most important application of these gravity and magnetic measurements will be to the study of the structure and evolution of the continents. The mission will give the first comprehensive coverage of the areas of greatest tectonic interest: the collision belts of the Himalayas and the Andes, and rift zones such as that in East Africa. Most of these areas cannot be surveyed by any other means. Understanding these major formational processes is essential to comprehending the state and evolution of the continents.

The GRM will also contribute to understanding of the sub-oceanic solid earth. It will give greatly improved coverage of both gravity and magnetic fields at the continental edges, which are important to ocean crust and lithosphere evolution, and of the magnetic field in the southern hemisphere and polar regions.

GRM will give profound insight into the deep interior of the Earth. The gravity field will elucidate the pattern and energetics of the thermal convection in the mantle which drives the plate motions. The magnetic field and its temporal variation will constrain models of the geodynamo in the fluid outer core.

The GRM is essential to the full utilization of the next generation of altimetric satellite, the TOPEX, by providing the geoid to which sea surface heights are referred for studies of oceanic circulation.

Further applications of the GRM are: (1) study of the lower thermosphere (taking advantage of its 160-km altitude); (2) study of externally generated variations of the magnetic field; (3) study of upper mantle conductivity; (4) improvement of orbit computation accuracy; and (5) improvement of reference frames for geodesy.

The main temporal constraint on GRM is the desirability of a launch well before the next solar maximum in 1991 in order to obtain longer orbital lifetime, greater accuracy for the internally-generated magnetic field, and contrast of conditions with those prevailing for MAGSAT in 1980. The 1988 level of solar activity will not be regained until 1994. No mission similar to GRM is being considered by any other country.

The Geopotential Research Mission will, like the Venus Radar Mapper (VRM), contribute importantly to the ongoing comparative study of the terrestrial planets.

INTRODUCTION

The Geopotential Research Mission (GRM) will measure the gravity and magnetic fields of the Earth at an altitude of 160 km. The minimum lifetime of the mission will be six months, which will give an average spacing between orbits at the equator of about 7 km. The DISCOS System will make the orbits drag-free. The perturbations of the gravity field will be inferred from range-rates between the satellites, while the scalar and vector magnetic field will be measured by standard magnetometers. The spacecraft orientation will be measured by star cameras. The anticipated accuracies and resolutions are: for the gravity field: 2 milligal (2×10^{-5} m/sec^2) and 100 km: and for the magnetic field: 2 nanotesla and 100 km (Goddard Space Flight Center, 1982).

The main documentation of the scientific rationale of the GRM is the Space Science Board (SSB) report "A Strategy for Earth Science from Space in the 1980's; Part I: Solid Earth and Oceans" (Committee on Earth Sciences, 1982). That report summarized the scientific goals for earth science into eleven catagories. Measurements by GRM would contribute significantly to four of these goals: III, Ocean Dynamics; VII, Plate Dynamics; X, Internal Structure and Composition of the Earth; and XI, Generation of the Earth's magnetic field. Because of the significant variations in the existing data base and the contributions which space techniques can make, the SSB report was organized into three objective areas. The rationale presented here is cast into a framework of objectives of which the first four are essentially a reorganization of those in the SSB report. In addition, the GRM will contribute to the aeronomy of the lower thermosphere, the study of the external magnetic field, orbit computation, and geodesy. Finally, we discuss how GRM should be coordinated with other space missions and related scientific efforts in the coming decade. The headings are:

I.   Dynamics and Structure of the Continents.
II. Dynamics and Structure of the Sub-Ocean Crust and Lithosphere.
III. The Deep Interior.
    A. The Mantle: Convection and the Gravitational Field.
    B. The Core: Generation of the Magnetic Field.
IV. Ocean Circulation.
V.   Other Applications.
    A. Aeronomy.
    B. External Magnetic Field.
    C. Orbit Computation and Geodesy.
VI. Coordination of GRM with other Missions and Studies.

I. Dynamics and Structure of the Continents

The principal planning document for solid earth dynamics is "Geodynamics in the 1980's" (U.S. Geodynamics Committee, National Academy of Science, 1980) which states (p. 15); "Continents, continental evolution and tectonics will be a principal focus for Geodynamics in the 1980's." The plate tectonic revolution had its birth in the ocean, and considerable progress continues to be made in understanding the structure and dynamics of the sub-oceanic crust and lithosphere, but it is certainly the consensus that the most important area for study now is the continents. By "continents" we mean not only the continental crust, but also the upper mantle to at least 200 km depth, since there appear to be perceptible variations to such depths, including systematic differences between sub-continental and sub-oceanic regions.

Both the gravity and the magnetic measurements by GRM will contribute greatly to the study of the continents, and both in two senses: (1) as quantitatively interpretable manifestations of subsurface physical conditions; and (2) as empirical indicators of geological variations. Normally, sense (1) is taken as primary: variations in the gravity field necessarily entail variations in rock densities, while shorter wavelength variations in the magnetic field necessarily entail variations in the remanent or induced magnetization of rocks. However, recent developments have emphasized sense (2) appreciably. Figures 1 and 2 of this report are recent compilations of the gravity and magnetic data available for the coterminous United States, extrapolated to spacecraft altitude, which show the correlation of gravity and magnetic features with geologic units.

Gravity and magnetic data of sufficient density to compile similar maps are available for most of Canada, Europe, and Australia, but not for the remaining 80% of the Earth's land area. Some of this four-fifths has been measured, but the data are not available for scientific research. Unfortunately, the inadequately mapped regions include most of the highly interesting tectonic areas such as the collision zones of the Andes and the Himalayas.

The 1982 SSB Report "A Strategy for Earth Sciences from Space in the 1980's" gave as a primary scientific objective "To measure the Earth's gravitational field from global scales to wavelengths of 200 km or less," and stated that "determination of an improved gravitational field through space measurement should be an objective of highest priority..." The reason for the emphasis on determination over a great range of wavelengths is partly the great variety of features to whose interpretation gravity can contribute; on the continents, features such as mountain ranges, sedimentary basins, rifts and shield areas. But the reason is also that the support mechanisms associated with a particular structure can be inferred only if there is information from a broad spectral range. Passive support of a topographic feature is by a combination of two mechanisms: (1) lithospheric flexure, which depends on the elastic strength of the lithosphere, and (2) isostasy, which entails "compensation," a mass deficiency at depth to match a mass excess on the surface, and vice-versa. With data at only one wavelength, these mechanisms cannot be distinguished. With data over a broad spectrum for a region reasonably homogeneous in material properties, solutions can be found for plausible combinations of lithospheric flexure and isostasy. In general, continental features of limited extent are supported more by the flexural rigidity of the lithosphere than are broad features, while geologically older features tend to be

FREE–AIR GRAVITY FIELD AT 160 KM ALTITUDE

(1 mgal CONTOUR INTERVAL)
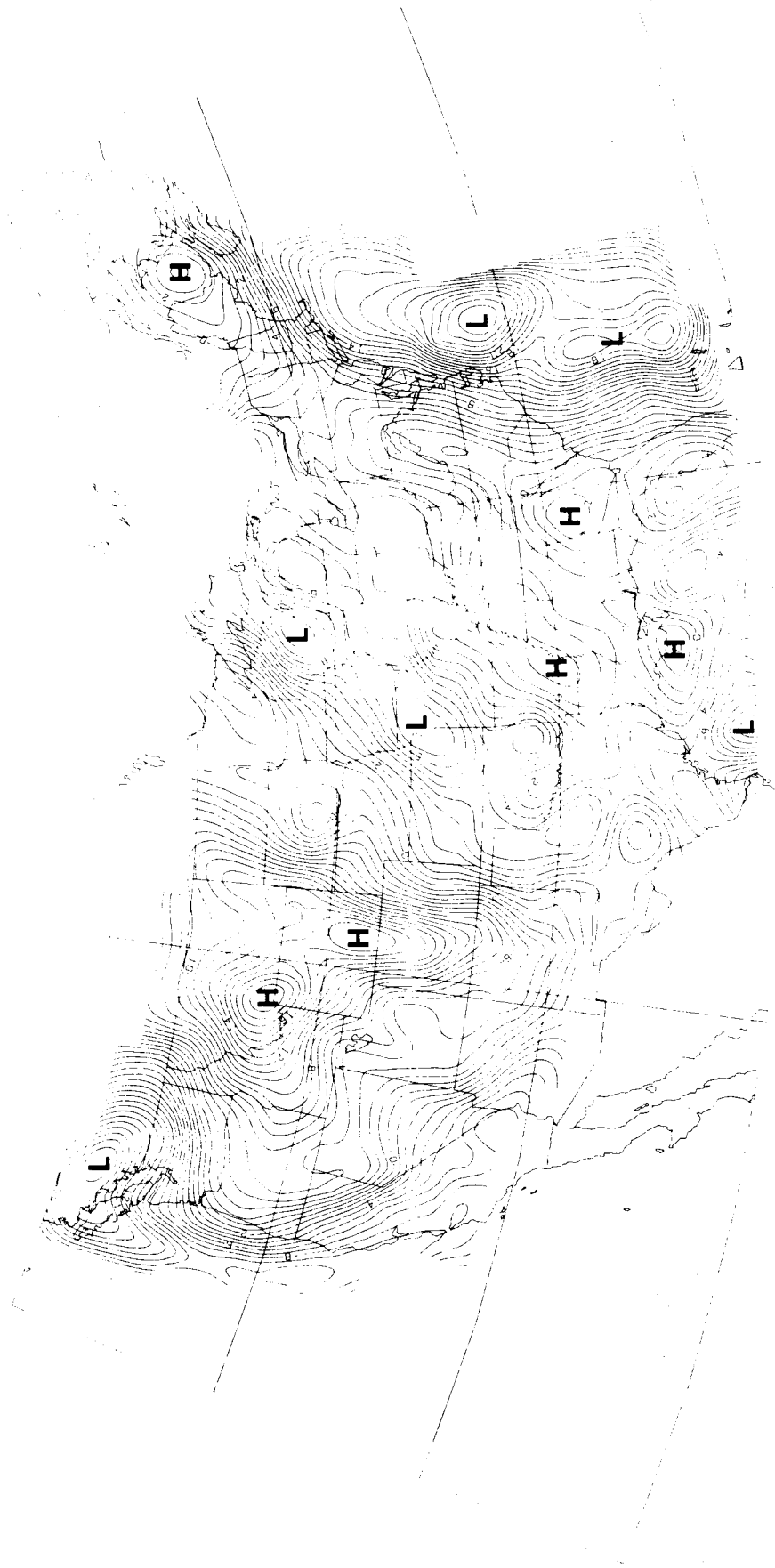
MAGNETIC ANOMALY FIELD AT 160 KM ALTITUDE

(5 nT CONTOUR INTERVAL)
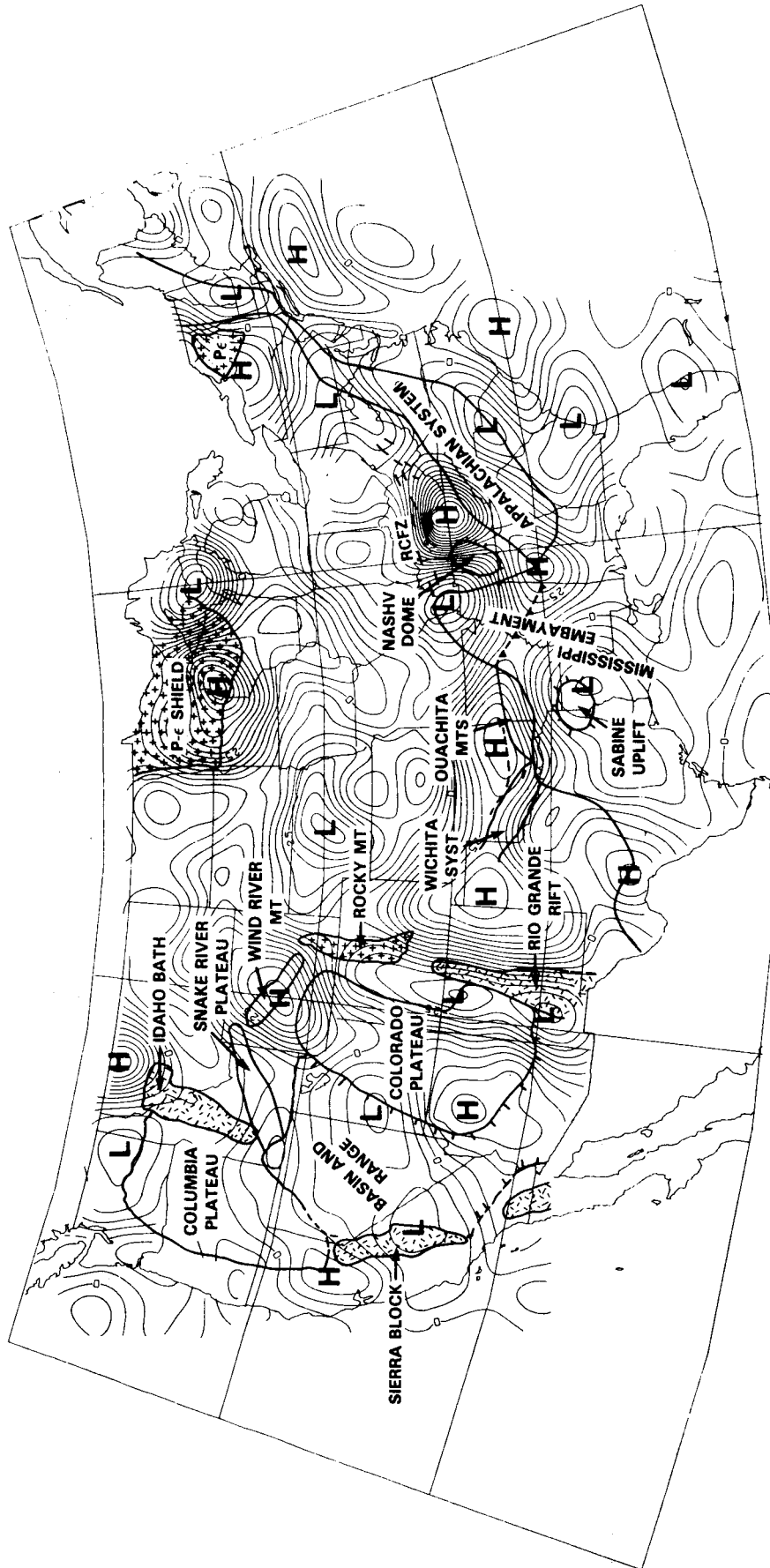
supported more by flexure than younger features. Over more rigid areas, the gravity field reflects relatively more upper mantle properties; over more flexible, crustal properties.

The response properties of flexural rigidity and isostatic compensation are only part of the picture. To create collisional mountain ranges, uplifted plateaus, sinking basins and offset faults, driving forces are required. Normally these forces are generated by mantle convection, discussed in Section III.A below. But usually a relatively simple assumption can be made about the underlying forces, based on plate tectonics or other broad constraints, and the problem becomes estimation of the details of response of the continental crust and lithosphere. Often these details depend on past history; tectonic phenomena tend to occur where previous events have created an obstacle. The most evident example is a subduction zone, where oceanic lithosphere is forced down because the continent is more buoyant. Because contemporary geodynamics interacts so strongly with geologic structure from the past, the two senses of data utilization given above tend to overlap.

Emphasis has been given to the wavelengths of features in the gravitational field. But there must also be signal above a measurable threshold in order for geophysical interpretation to be made. This question was addressed by the GRAVSAT Users Working Group, which in its August 1980 report produced a table including the following continental features:

Feature Type	Wavelength (km)	Accuracy (mgal)
Sedimentary Basins	10-300	3-6
Batholiths	20-300	3-6
Mountain Ranges	20-1000	8-10
Subduction Zones	50-1000	10-12
Shields	50-800	2-3

$$(1 \text{ mgal} = 10^{-5} \text{ m/sec}^2)$$

These accuracies are within the capability of GRM for wavelengths of about 100 km or more. Consequently the 2-mgal GRM system should obtain significant scientific information concerning these structures.

The magnetic field at wavelengths less than about 3000 km is generally believed to be caused by sources within the crust and upper mantle. However, there are difficulties in accounting for the field intensity from these shallow sources, because some of these wavelengths may come from the core; this is discussed in Section III.B below. A more accurate survey, such as that by GRM, would help to resolve this difference.

Physically, the magnetic anomaly field is related to the gravity field in that the magnetic susceptibility is inversely dependent on the temperature, so that magnetic field intensity might be expected to be positively correlated with the intensity of gravity anomalies. In actuality this correlation is masked by other complications. The value of the shorter wavelengths of the magnetic field thus tends to be the empirical one of highlighting geologic structures which otherwise would be obscured by the effects of erosion and sedimentation, such as the large positive anomaly in Kentucky and Tennessee

(Figure 2), which marks the site of a Precambrian rift. In tectonically stable areas, such as shields, gravity anomalies have the same property. If the lithosphere is cold and thick enough, it can support features of a few tens of kilometers dimension almost indefinitely. A probable example is the mid-continent geophysical anomaly, the feature in Figure 1 extending several hundred kilometers southwesterly from the western end of Lake Superior. In younger continental crust, magnetic anomalies are often controlled by the thickness of the crustal material which is below the Curie temperature of the magnetic minerals, and therefore reflect the pattern of heat flow.

Rifts, or "failed" rifts (aulacogens), and their associated hot spot swells, are of particular interest, since they are the sites of intense volcanism, and of mineral accumulations and petroleum deposits. A Precambrian rift has recently been identified cutting across Missouri, from a combination of gravity, magnetic, and thermal infrared imaging of the Heat Capacity Mapping Mission (HCMM). This ancient rift, of possible economic significance, is not evident in the surface topography or sediments. Other rifts in the United States have been discovered using surface gravimetry and aerial magnetometry, and have been inferred on other continents from MAGSAT data. A combination of the gravity field and magnetic field measurements by GRM would allow many more continental rifts to be discovered, modelled, and their geologic evolution inferred.

Mountain ranges show impressive variations in their gravitational signature. For example, the Alps and the Appalachians correlate with belts of positive and negative gravity anomalies with widths of a few tens to a few hundreds of kilometers and amplitudes up to 100 milligals. This negative-positive anomaly "couple" has recently been interpreted in terms of the mass loads that act on the lithosphere during mountain building, and the flexural properties of the lithosphere. The positive anomalies appear to arise from buried loads, such as abducted "flakes" of crust, which developed on the leading edge of the underthrust plate during the mountain building. The negative anomalies seem explicable as resulting from flexing of the lithosphere in response to both surface and sub-surface loads, such as fold-thrust sheets. By comparing the amplitude and wavelength of the observed gravity anomaly "couple" to calculated profiles based on various flexural models, it has been possible to estimate the flexural rigidity of continental lithosphere under mountain ranges. Thus, for example, the Appalachians appear to have an appreciably greater lithospheric strength than the younger Alps. These estimates of lithospheric strength and its relationship to the age of the "basement" and age of the orogeny provide important information on the rheology of the lithosphere. Because mountain ranges are of such large dimensions, GRM should enable estimates of the flexural properties of the continental lithosphere in their vicinity.

Sedimentary basins are significant as the location of petroleum and mineral deposits. The thermotectonic history of a sedimentary basin (such as those of the North Sea and Alberta) is a complex interaction of loading, cooling, and flexure. Gravity measurements have contributed greatly to understanding the role of flexure in the evolution of basins. It appears feasible for GRM to resolve significant features in relatively large continental basins, such as the Appalachian, the North Sea, and the Russian Platform.

In addition to defining the regional context for possible exploration targets, GRM would be of appreciable service to mineral exploration by furnishing a base for merging surface magnetic and gravity survey information over large areas. Its coterminous global coverage would provide the synoptic patterns to which detailed studies of limited areas could be matched and integrated. This would greatly ease a major problem of joining adjacent studies done by different workers on different scales with different datum corrections and assumptions. The GRM would also furnish an objective measure of the regional trends, which must be subtracted from surface surveys to identify target anomalies. Providing this common base would eliminate a current source of bias in applied geophysical analyses.

The two data sets of gravitational and magnetic potential, after suitable filtering, are useful for inferring tectonic histories from past epochs, often hundreds of millions of years old. This application is particularly true for magnetic anomalies, since they are not as susceptible to obliteration by isostatic adjustment. Thus, for example, matching of anomalies over different continental areas now separated by young ocean basins (e.g., South America and Africa) can be of use in reconstructing past continental configurations.

The examples presented above are only a few of the continental tectonic problems to which gravity and magnetic data apply. Despite the boon of satellite altimetry over the oceans, the majority of studies have continued to be of continental problems (as evidenced, for example, by papers in journals such as the Journal of Geophysical Research). This persistence of interest in the continents is partly because there exists other applicable data (geological, seismological, etc.), but mainly because most of the interesting important problems occur there. The controllers of oceanic tectonics are the subduction zones associated with great compressive belts, such as the Andes and the Himalayas. The variety of tectonic phenomena on the continents is much greater, because of the variety of circumstances arising from their three billion year histories. Virtually all economically usable mineral deposits occur in intracontinental and continental margin environments. Because of this abundance of tectonic problems associated with continents, there is a large community of scientists who will welcome the gravimetry and magnetometry which GRM would bring to the poorly surveyed eighty percent of the continents.

GRM satellite-to-satellite range-rate is, at present, the only feasible means of obtaining accurate gravity measurements over a major part of the continents for which data are unavailable, and which include the most important features. The increase in resolution in measurement of the magnetic field over that determined by MAGSAT is significant. Both of these measurements will enable the modelling of crustal and lithospheric structure and their evolution.

II. Dynamics and Structure of the Sub-Oceanic Crust and Lithosphere

The ocean surface altimetry generated by the GEOS-3 and SEASAT missions has contributed greatly to our understanding of the evolution of the oceanic lithosphere as it moves away from the rises at which it is generated. It is also being applied successfully to subduction zones in regions of ocean-under-ocean lithosphere subduction, such as the Tonga Trench. As mentioned above, subduction zones are most important, since they probably control the oceanic

plate motions. However, the data are incomplete for ocean-under-continent subduction (such as the Andes, or the western ocean-under-marginal-basins sub-duction, where an extensive island arc has evolved (such as the Indonesian Archipelago). Another problem of the oceanic marginal zone which needs better understanding is the development of back-arc basins (such as the Philippine Sea), which in some cases may be developing into oceans themselves.

Aside from the aforedescribed problems of marginal zones, there are sev-eral problems of tectonic under the open oceans where satellite-to-satellite range-rate, with its different spectral characteristics, could be a valuable check and supplement of the altimetry. The correct inferences as to loading and differentiation histories and support mechanisms for sea mounts, ocean island volcanic accumulations, aseismic ridges, etc., often depend on rather subtle details in the spectrum, which are missed because of either inadequate accuracy of the GEOS-3 data or inadequate density of the SEASAT data.

Magnetic anomalies over the oceanic crust were the key which unlocked the plate tectonic pattern. Sea floor spreading anomalies are of too short wave-lengths to be sensed by GRM, but there are longer wavelength anomalies whose sources are still unknown. For example, MAGSAT data show a significant mag-netic anomaly associated with the bend in the Hawaiian-Emperor seamount chain, as well as other large anomalies in the western Pacific. But much of the oceanic crust appears to give only small signals at MAGSAT altitudes. GRM would greatly improve the signal-to-noise ratio by measuring closer to the source. The minimum resolution length of 100 km will allow the anomalies pro-duced by linear oceanic features - such as aseismic ridges, seamount chains, and submarine plateaus - to be seen much more clearly than at the higher alti-tude of MAGSAT.

GRM's main contribution to understanding oceanic evolution and tectonics will be through its measurement of the gravitational effects at subduction zones, but other problems, such as flexure across sea mount chains and mag-netic properties of the oceanic crust and upper mantle, can be studied as well.

III. The Deep Interior

A. The Mantle: Convection and the Gravity Field

The problem of mantle convection is fundamental to understanding the evo-lution of the Earth. The outgassing of the oceans and atmosphere, the differ-entiation of the crust, volcanism, and all tectonics - continental complica-tions as well as oceanic plates - are ultimately dependent on energy sources within (and possibly below) the mantle, and upon the transport of this energy in the mantle by thermal (plus some compositional) buoyancy. The oceanic crust and lithosphere are part of this convection: they are its uppermost boundary layer, coming to the surface at the rises and returning to the inter-ior at subduction zones. Most oceanic crust, as well as its associated litho-sphere, must be recycled to the interior. The continental crust and sizeable pieces of sub-continental mantle ride on top of the convective system. The velocities of the system are centimeters per year: the heat delivery is an average of 0.08 watts/meter^2. These values, together with the thermal and rheological properties of rocks, indicate that the system could be much more

complicated than the smoothest flow necessary for observed plate motions. Phenomena such as changes in the plate tectonic pattern every 10-20 million years, long-term episodicity of volcanism in tectonically complex areas such as western North America, exceptionally high heat flow on the continental side of subduction zones, and higher than predicted heat flow in ocean basins, all suggest that there are secondary scales of mantle flow not directly connected to the precisely measured plate tectonic pattern. What is needed are measurements which see <u>through the lithosphere and into the mantle.</u> The gravitational field is such a measurement. However, gravity in a sense sees too much: it is the integration of attractions throughout the solid earth. Hence it is essential, first, to measure it over as broad a spectrum as possible; and, second, to strip off as much as can be properly explained by topography and density variations in the crust and lithosphere.

The gravity field is a direct constraint only on contemporary convection. The problems of greatest concern are mostly dependent on long-term evolution. However, the character of mantle convection has doubtless evolved slowly over the last few billion years. The energy sources are declining slowly: by a factor of about fifty percent in the last three billion years. The most crucial question of these last three billion years - the extent to which mantle convection is separated into separate upper and lower mantle systems - will probably be inferred largely from the effect of this separation on manifestations of contemporary convection, such as the gravitational field.

For essentially the foregoing reasons, the SSB 1982 report stated: "Determination of the Earth's gravity field over a wide range of spatial scales is of importance for solid earth dynamics because it is likely to provide direct information of the planform of mantle convection ... <u>An improved gravitational field through space measurement should be an objective of highest priority for the 1980's.</u>"

The theoretically predicted complexity of mantle convection, as well as the strong temperature dependence of rock rheology, make it a difficult problem for computational modelling. Progress depends on a rapidly developing dialogue between the fluid dynamicists and those who generate constraints on the models, such as seismologists, isotope geochemists, petrologists, geologists, and others. Theoretical predictions of the gravity signal from forward models have been made since the mid-1960's, and attempts at applying gravity variations as boundary values in inverse models are under way. At the present rate, there will exist by 1988 the capability of using gravity variations as effective constraints on mantle convection models to the same extent as they are now being used for lithospheric models. This capability depends on improvements in computer capacity and knowledge of material properties at high pressure as well as fluid dynamical insight (see the U.S. Geodynamics Committee 1980 report previously cited). Hence, by 1988, it is desirable to have a more complete data set to match these models, and to generate improvements.

B. The Core: Generation of the Magnetic Field.

It has long been known that the Earth's magnetic field changes rather rapidly, such that at any one place these changes can be detected within a few months. The secular variation of the Earth's magnetic field is one of the few evidences of the geodynamo, the motions of material in the liquid outer core which maintain the magnetic field. Much has been done by looking at records

obtained from magnetic observatories, but the small number of observatories (less than 200) and the very uneven distribution over the surface of the Earth (most are in Europe - the South Pacific, Africa, and a large part of Asia and Antarctica are virtually unsampled) means that it is impossible to derive a complete representation of the time-varying field from such data. Spherical harmonic models of the Earth's magnetic potential have been produced from time to time, starting with Gauss in 1839. Magnetic observatory data have been supplemented occasionally by repeat stations, surface ship measurements, aero-magnetic data, and satellite data (mainly from the POGO satellites). But the patchy nature of these data, and the fact that the POGO satellites measured only total field magnitude, meant that the measurements of scalar and vector field collected by MAGSAT produced a far better picture of the main magnetic field that had been available prior to 1980.

In order to determine the nature of the time-varying changes of the magnetic field, it is necessary to obtain a second accurate measurement of the field at a later epoch. This measurement is precisely what GRM will achieve. The time span between MAGSAT and GRM will be about nine years, which is adequate for very significant changes in the various components to occur. It was found that over the 7.5 month life span of MAGSAT, many of the spherical harmonic coefficients of the potential required time-varying terms in order to model the observed field accurately. However, the baseline of these measurements was not long enough to allow these time terms to be measured accurately. But a baseline of nine years will provide a large enough change that an accurate measurement of many of the changes will be accomplished. Changes in the higher degrees of spherical harmonics will need even longer periods of time, and in any case they may not change in a coherent manner. However, based on an analysis of previous attempts to measure secular variation, it should be possible to determine the secular variation of spherical harmonic components up to degree 12 (wavelength 3300 km) to an accuracy of about 0.1 nT/yr using a nine year baseline. This will be a significant improvement over previous attempts, which have usually been inaccurate beyond degree 8.

Once a reliable model of secular variations is obtained at the Earth's surface, it can be extrapolated, along with the field itself, down to the core-mantle boundary. These two fields can then be used to constrain motions in the fluid core, which are not inferrable from seismological or other data. This pattern of motion in the top boundary layer of the core is of great interest in unravelling the nature of the dynamo, as well as being important to forecasting future magnetic fields.

It should also be possible to look at some of the higher-degree harmonics of the potential to see whether any significant changes have taken place since MAGSAT. It is generally believed (see Section I) that harmonics higher than degree 14 represent sources from within the crust. However, if any of these harmonics change with time, this will be excellent proof that they have sources within the core. Although most of the time-varying changes in the higher-degree harmonics will not be capable of being measured, due to the resolution of the method, some of the changes should be larger than average and thus capable of being detected, should they exist. Thus a second very accurate look at the field provided by GRM data will help solve this major problem concerning the source of the intermediate wavelength components of the field.

Longer wavelength variations in the gravity field from GRM measurements will constitute strong constraints on models of mantle convection. The longer wavelengths in the magnetic field observed by GRM, with those from MAGSAT, will produce a very accurate representation of the secular variation, which will constrain models of motion in the fluid core.

IV. Ocean Circulation

The SSB study "A Strategy for Earth Science from Space in the 1980s," 1981, states: "The primary scientific objectives for the study of ocean dynamics from space for the next decade, in order of priority, are:

1. (a) To measure the time-variable sea-surface elevation;
   (b) To measure the time-independent sea-surface elevation relative to the geoid..."

The sea surface differs from the geoid because of currents, wind stress, salinity, and temperature variations. These departures, called the sea surface topography, occur over a wide range of length scales from 30 km to basin-wide, and over time scales from days to essentially constant. Preliminary estimates of this topography to about 50 cm accuracy have already been made for basin-wide variations using SEASAT altimetry and an independent satellite geoid. The errors of about 50 cm reside mainly in the SEASAT orbit and the geoid, and negligibly in the radar altimetry itself, which probably achieved its design accuracy of 10 cm.

It is desirable to measure the sea-surface topography to 2 cm, the design goal of TOPEX, over as wide a range of length and time scales as possible. Table IV-1 lists the geoid height accuracies achievable for three spatial averaging sizes, while Table IV-2 gives oceanic current scale sizes and estimates of concomitant geoid height accuracies required to determine the currents (TOPEX Working Group, 1981).

TABLE IV-1

Averaging Size (degrees)	Scale at Equator (km)	Geoid Height Accuracies (cm)
2 x 2	220	2
1 x 1	110	4
.5 x .5	55	16

TABLE IV-2

Region	Transverse Size (km)	Surface Elevation (cm)	Geoid Requirements Length Scale (km)	Geoid Requirements Height Scale (cm)
Western Boundary Currents	200	150	50	10
Return from Western Boundary Currents	2000	150	50	10
Antarctic Circum-polar Current	1000	100	100	10
Equatorial Currents	1000	35	100	3.5
Basin-Wide Circulation	2000	50	200	5
Pacific-Wide El Niño	5000	100	500	10

It may be seen that current scale sizes of order 100 km (half wavelength) require geoid height estimates of approximately 4 cm. Such a measurement yields a surface geostrophic current error of 4 cm/sec at mid-latitudes. It should be noted that geoidal definition to a full wavelength of 200 km implies a horizontal resolution scale of 32 km, which is very close to the internal Rossby radius of deformation of approximately 30 km that characterizes most baroclinic ocean currents. Thus, GRM can provide a geoid whose definitions on both horizontal and vertical dimensions can in principle allow TOPEX or similar altimetric satellites to separate oceanic setup from geoidal undulations, down to the smallest scales of interest.

The relationships between GRM and TOPEX are further discussed in Section VI below. The impact of measurements of both the mean and fluctuating portions of oceanic surface elevations will be to allow greatly improved estimates of global heat transport by the ocean to be obtained; this transport is thought to carry toward the poles of the order of one half (or more) of the excess solar energy deposited in the tropics. This transport is an extremely important mechanism in establishing global climate and its variability. Both the mean current and its fluctuations enter into the transport process, the latter through nonlinear turbulent stresses; and while the energy of the current fluctuations in some parts of the ocean significantly exceeds the mean, the net eddy transport of either fluid or heat by fluctuating currents is estimated to be of the same order as the mean. Thus it is essential to determine both mean and variance if world ocean circulation is to be understood.

The GRM gravity and geoid information are essential for the achievement of the Space Science Board objectives for global sea surface elevations and attendant geostrophic current measurement.

V. Other Applications

A. Aeronomy.

Measurements by the Dynamics Explorer (DE) spacecraft, combined with ground-based observations, are defining the global circulation and structure in the F-region, about 300 km altitude. This circulation is energized by solar EUV at low- and mid-latitudes, but is strongly controlled by ion drag at high latitudes. Numerical models of magnetospheric convection which predict this behavior at 300 km altitude require arbitrary source parameters, but generally predict much different temperature and circulation patterns in the lower thermosphere, below 200 km altitude. Solar EUV and ion drag are less important at these lower elevations, while other effects, such as dissipation of tides and waves and heating and cooling by nitrogen oxide, are relatively more important. The few measurements which have been made in the lower thermospheric region indicate that enormous shears and extreme velocities at high latitudes can occur, and these have important implications for the global thermospheric circulation and energy budget.

The SSB report, "Solar System Space Physics in the 1980's: A Research Strategy" (Committee on Solar-Terrestrial Relationships, 1980), pointed out the need for a thermospheric dynamics satellite to operate with the incoherent scatter radar chain and the optical Fabry-Perot network to derive the global dynamic properties of the thermosphere. Current investigations should, in the coming decade, improve understanding of the thermosphere as a modulator and redistributor of solar wind energy, mass, and momentum into the Earth's upper atmosphere. However, in-situ observations of thermospheric dynamics are badly needed. Measurements of winds and densities at the low-altitude polar orbit of GRM are an exciting opportunity to provide global synoptic maps of the dynamics and structure of a region which is very important, but relatively unprobed.

B. External Magnetic Field.

The external magnetic field of the Earth arises from a complex system of electric currents flowing in the magnetosphere and ionosphere. Of particular interest are the currents which flow along magnetic field lines into and out of the polar regions. A vector magnetometer on a low-altitude spacecraft, such as GRM, would make it possible to study the directions and intensities of these currents, and their spatial and temporal variations. At a higher altitude, MAGSAT was the first satellite to measure these currents with a nearly absolute standard. This permitted study of the relationship between field-aligned currents and auroral electrojet currents.

Magnetic observations by GRM at 160 kilometers altitude would provide higher-resolution studies of the auroral electrojets, because they would be the closest observations to these currents ever made.

Studies of the external magnetic field are important to study of the Earth's interior in two ways. First, the study of the internally generated field depends on correct removal of the external field. At present, data taken during periods of external field disturbance are often useless for the study of the internal field generation. Second, temporal changes in the

external field enable estimates to be made of the electrical conductivity of the solid Earth, because they induce currents. The magnetic field produced by these induced currents should be strong enough at GRM altitudes to enable determination of regional variations in the electrical conductivity of the Earth. These variations in conductivity in turn indicate variations in temperature.

C. Orbit Computations and Geodesy.

These problems were addressed in the NRC study "Applications of a Dedicated Gravitational Satellite Mission" (Panel on Gravity Field and Sea Level, Committee on Geodesy, 1979). At that time, the critical needs were of two distinct types: (1) altimetric satellites such as GEOS-3 and SEASAT-1, and (2) positioning satellites such as LAGEOS, STARLETTE, and GPS. Both of these needs persist. In regard to satellite type (1), the requirement is more severe than ever, if TOPEX is to be implemented, since the altimetric accuracy contemplated (4 cm) is about what is estimated for one-degree mean geoid heights from satellite-to-satellite range-rate by the Gravsat Users Working Group in its report of August 1980.

Geodesy requires precise orbits, as discussed in the preceding paragraph. An independent desideratum is the attainment of a global datum for height measurements. For obvious practical as well as physical reasons, vertical locations within geodetic systems should be referred not to a reference ellipsoid or the Earth's center, but rather to an equipotential surface. Normally this specific equipotential surface is estimated from tide measurements. However, the mean sea level differs from an equipotential level by tens of centimeters, while for remote areas where control for mapping is by photogrammetry, the averaging out of tidal oscillations in the photos may not be feasible. Satellite positions and geoid heights accurate to centimeters could unify vertical datums, and establish them in remote areas. The determination of an accurate geoid from GRM data will be important to fully utilizing the Global Positioning System (GPS) to determine locations, since heights above the geoid are wanted.

GRM will provide significant information to aeronomers, complementary to that from the Dynamics Explorer, because of its low altitude. External magnetic fields will be better defined, and useful information about Earth conductivity will be obtained from the time-varying induced currents. The accurate gravity field generated by GRM will lead to more accurate satellite orbits and a more precise geoid, of value to geodesy as well as to oceanography.

VI. Coordination of GRM with Other Missions and Studies

The most important time constraint on GRM is the solar cycle. The next solar maximum is expected to be in 1991. In 1988, the average solar activity will be only about one-third as strong as the average during the maximum of 1991. Furthermore, since the increaase in solar activity is much more rapid than the decrease, it would be necessary to wait until about 1995 for a comparably low level. It is particularly desirable to orbit GRM during a solar quiet time because MAGSAT was flown during a time of high solar activity in

1980; for a significant fraction of its lifetime, the external field distur-
bances were so large as to make the data collected of limited use in defining
the internal field. Thus a GRM mission launched in late 1988 would constitute
a very good compromise between the baseline time length from MAGSAT for secu-
lar variation studies, and a low solar activity to get good signal-to-noise
ratio. It would also be a good interval before the Magnetic Monitoring
Mission proposed for the 1990's. Furthermore, if GRM is postponed to 1995,
the 15-year time interval after MAGSAT will lose some higher-frequency varia-
tion in the secular variation.

The indirect nature of inferences from the gravity and magnetic fields
makes it essential that they be used in conjunction with other data. By far
the most important data type is topography: first, the elevations, to calcu-
late the attracting effect of the topography; second, imagery, to provide the
visible context of the gravimetry and magnetometry. The elevations required
must be accurate to a few meters for area means comparable to the resolution
of the gravimetry. In many areas of interest, such as the Soviet and Indian
parts of the Alpide Belt, this accuracy can be satisfied by existing maps. In
others the requirement can be met by systems of moderate accuracy, such as the
GEOS-3 and GEOSAT altimeters, or the Large Format Camera (LFC), scheduled to
be flown on the Space Shuttle in August 1984. The imagery of relatively
undeveloped areas, which is the foremost application of GRM, is best obtained
by radar systems, since many of these are covered by vegetation (e.g., the
Amazon Basin). Furthermore, in areas not so covered, it is desirable to infer
subsurface features, such as the relics of valleys in the eastern Sahara found
by SIR-A. The obvious tool is Shuttle Imaging Radar B (SIR-B), scheduled for
the Space Shuttle in August 1984. SIR-B and GRM will make a natural couple,
and the two data types in combination should constitute a significant advance
in comprehensive examination of major tectonic areas such as the Hundu Kush -
Pamir - Himalaya - Tibetan Plateau Complex or the Andean chain, which are so
important to the global tectonic picture but so inaccessible to ordinary means
of survey.

While existing data plus LFC, SIR-B, etc., will complement the highest-
priority objectives of GRM - the dynamics and structure of the continents -
the study of the suboceanic crust and lithosphere will continue to be limited
by the sparseness of bathymetry in many areas. This situation will improve
with time. However, the strongest driver for this application of GRM is to
complete the data for land-covered parts of subduction zones.

For the deep applications of GRM described in Section III (Mantle Con-
vection and Core Geodynamo) the pacer is the development of theoretical
insight and computational models. As discussed above, mantle convection
modelling should be able to use detailed gravitational fields within a half
decade, while hydromagnetic theorists are already anxious for better data on
secular change in the magnetic field, for which a GRM nine years after MAGSAT
would be ideal.

The application of GRM data to ocean circulation depends, of course, on
an accurate altimetric satellite, for which role TOPEX is proposed. Objective
1(a) of Section IV, the time-varying field, can be partially achieved to an
estimated accuracy of 14 cm using precisely repeating tracks of the TOPEX
orbit in an inclination designed to avoid tidal effects. At present, a repe-
tition interval of ten days and an inclination of 64 degrees are planned. The

14 cm error arises almost entirely from the radial component of the satellite position. This estimate assumes intensive tracking by the TRANET Doppler network and orbit computation using the best available gravity data (JPL Study Team, 1982). However, the balance of objective 1(a) and objective 1(b), the time-invariant field, cannot be attained to better than the existing 50 cm accuracy without a greatly improved gravity field, which GRM would provide. This gravity field would contribute in at least two ways: (1) by furnishing a more accurate geoid, and (2) by enabling computation of more precise orbits for TOPEX (TOPEX Science Working Group, 1981). Other ways in which GRM may contribute to the TOPEX mission are: (3) by enabling more effective deployment of surface ship measurements complementary to the TOPEX altimetry, and (4) by freeing TOPEX from restriction to the precisely repeating ground track. Improvement (3) would come through use of the GRM gravity field for the orbit and geoid with Seasat altimetry, furnishing sea surface topography good to about 10 cm, which would enable more careful planning of the surface ship placement. Contributions (1), the geoid, and (2), the orbit, could eventually be realized by launching GRM subsequent to TOPEX. The improved orbit accuracy, (2), could be partially achieved through use of the Series-X/Global Positioning System, which is currently under development. However, contribution (3), ship deployment planning, could not be attained without GRM prior to TOPEX, while contribution (4) with TOPEX prior to GRM would require an assurance difficult to imagine.

As discussed in Section V.B, the low altitude of GRM would make it of great benefit to aeronomy, providing measurements complementary to those of the Dynamic Explorer spacecraft at 300 km, and greatly assisting an ongoing theoretical and observational effort in upper atmosphere circulation.

A final virtue of GRM which should be mentioned is that, to the knowledge of this working group, it is unique: no other satellite-to-satellite range-rate system is under consideration, either in the Department of Defense or overseas. For the gravitational part of the mission, the principal system under development is the cryogenic gravity gradiometer. However, the gradiometer is still at an early stage of laboratory development. It is not known whether certain fundamental difficulties will be overcome, and, at best, the gradiometer would not be ready for space flight until well into the 1990's.

VII. Concluding Remarks

GRM will be capable of measuring the gravity and magnetic field of the Earth from the longest wavelengths down to a half wavelength of about 100 km. GRM's sensitivity to an extended spectrum should enable a large variety of crustal problems to be studied. The gravity and magnetic response of mountain ranges, sedimentary basins, rifts, and other structures will be measured. These measurements can then be used to model these features and constrain their tectonic history.

The longer wavelengths of the gravity field will be valuable for modelling the convection which occurs within the mantle. The long-wavelength spectrum of the magnetic field will allow an accurate model of the core field to be produced. Comparison of this model with that produced by MAGSAT nine years earlier will give the best information ever available on the secular variation of the magnetic field.

The gravity data over the oceans will provide a gravitational geoid, to which sea surface heights measured by TOPEX can be referred. These heights will give information on the time-independent oceanic circulation. The pattern of external magnetic fields and information on the circulation pattern in the lower thermosphere will also be measured by GRM. The more accurate measurement of the gravity field by GRM will enable significantly more accurate calculations of orbit parameters of other satellites, including TOPEX. A launch of GRM in 1988 would be timely from several points of view. First, it will be long enough after MAGSAT to allow very accurate measurements of the secular variation of the Earth's magnetic field to be made, without getting into a time of high solar activity, which tends to produce larger external fields and therefore poorer information about the internal field of the Earth. Second, if flown before TOPEX, GRM will improve planning for TOPEX, and allow calculatons on the time-independent oceanic circulation to be commenced immediately after TOPEX is launched. Third, there are a number of other developments in the various fields of geophysics relevant to the GRM which argue for a launch in 1988, as outlined in Section VI of this report.

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